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# Polystyrene- $\text{Al}_2\text{O}_3$ composite solid polymer electrolyte for lithium secondary battery

Yu-Jeong Lim<sup>†</sup>, Yu-Ha An<sup>†</sup> and Nam-Ju Jo<sup>\*</sup>

## Abstract

In a common salt-in-polymer electrolyte, a polymer which has polar groups in the molecular chain is necessary because the polar groups dissolve lithium salt and coordinate cations. Based on the above point of view, polystyrene [PS] that has nonpolar groups is not suitable for the polymer matrix. However, in this PS-based composite polymer-in-salt system, the transport of cations is not by segmental motion but by ion-hopping through a lithium percolation path made of high content lithium salt. Moreover,  $\text{Al}_2\text{O}_3$  can dissolve salt, instead of polar groups of polymer matrix, by the Lewis acid-base interactions between the surface group of  $\text{Al}_2\text{O}_3$  and salt. Notably, the maximum enhancement of ionic conductivity is found in acidic  $\text{Al}_2\text{O}_3$  compared with neutral and basic  $\text{Al}_2\text{O}_3$  arising from the increase of free ion fraction by dissociation of salt. It was revealed that PS- $\text{Al}_2\text{O}_3$  composite solid polymer electrolyte containing 70 wt.% salt and 10 wt.% acidic  $\text{Al}_2\text{O}_3$  showed the highest ionic conductivity of  $9.78 \times 10^{-5} \text{ Scm}^{-1}$  at room temperature.

**Keywords:** polystyrene,  $\text{Al}_2\text{O}_3$ , solid polymer electrolyte, polymer-in-salt system, lithium secondary battery

## Introduction

A lithium secondary battery using solid polymer electrolyte [SPE] is an attractive energy source for portable devices since the use of SPE makes the fabrication of safe batteries possible and permits the development of thin batteries with design flexibility. Most of the efforts to date have focused on poly(ethylene oxide) [PEO] as the host material for SPE [1-3]. However, it has a major drawback of having a low ionic conductivity ( $10^{-8}$  to  $10^{-5} \text{ Scm}^{-1}$ ) at room temperature [4]. Thus, many researchers [5-7] have focused on the SPE consisting of the polymer with low glass transition temperature [ $T_g$ ] and moderate concentrations of salt in order to overcome the low ionic conductivity of SPE, but high ambient conductivity has not yet been reached. Low ionic conductivity can be achieved from the fact that the ionic mobility strongly depends on the polymer segmental motion and that the cation transport number is low in the SPE at a high salt concentration. Therefore, new materials with unconventional conduction mechanisms are clearly needed [8].

In common SPEs, a polymer which has polar groups in the chain is necessary for electrolyte formation. The polar groups dissolve lithium salt and coordinate cations. The cations can move between coordinating sites in one chain or in neighboring chains, promoted by the segmental motion [9]. From this point of view, a polymer which has nonpolar groups is not suitable for the polymer matrix in common SPEs. However, in this new composite SPE consisting of polystyrene [PS] and having nonpolar groups,  $\text{LiCF}_3\text{SO}_3$  and  $\text{Al}_2\text{O}_3$  with polymer-in-salt system, the transport of cations is done by ion-hopping through an ion percolation path made of high content lithium salt instead of segmental motion. Moreover,  $\text{Al}_2\text{O}_3$  can cause conductivity enhancement depending on the nature of the filler surface group [10]. In this work, the ionic conductivity of PS- $\text{Al}_2\text{O}_3$  composite SPE according to the salt content was checked, and the effect of  $\text{Al}_2\text{O}_3$  type and content on ion conduction properties in PS-based composite SPE was investigated.

## Experimental section

### Materials

Polystyrene (Sigma-Aldrich Corporation, St. Louis, MO, USA) with a number average molecular weight ( $M_n$ ) of 170,000 was used as received without undergoing

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further purification process. As salt,  $\text{LiCF}_3\text{SO}_3$  (Sigma-Aldrich Corporation) was dried and stored in a desiccator under nitrogen. Three types of aluminum oxides [ $\text{Al}_2\text{O}_3$ ] (Sigma-Aldrich Corporation) with acidic, neutral, and basic surface groups as fillers were also used. As an organic solvent, *N*-butyl acetate (Junsei Chemical Co., Ltd., Chuo-ku, Tokyo, Japan) was used in order to dissolve the materials.

#### Preparation of PS-based composite SPE films

An appropriate amount of PS was introduced into *N*-butyl acetate and stirred for 24 h; after that, a definitive amount of  $\text{LiCF}_3\text{SO}_3$  was added to the solution and stirred again for 24 h. At the same time of the PS/ $\text{LiCF}_3\text{SO}_3$  solution preparation, 5, 10, 15, and 20 wt.%  $\text{Al}_2\text{O}_3$  were added to *N*-butyl acetate. Then, the solution was sonicated for 10 min and stirred for 24 h for dispersion. PS-based SPE was prepared by mixing the PS/ $\text{LiCF}_3\text{SO}_3$  and  $\text{Al}_2\text{O}_3$  solutions for 4 days. The solutions were directly cast on  $3 \times 3 \text{ cm}^2$  stainless steel plates after mixing and then allowed to dry in a vacuum oven for 5 days at  $40^\circ\text{C}$ .

#### Characterization

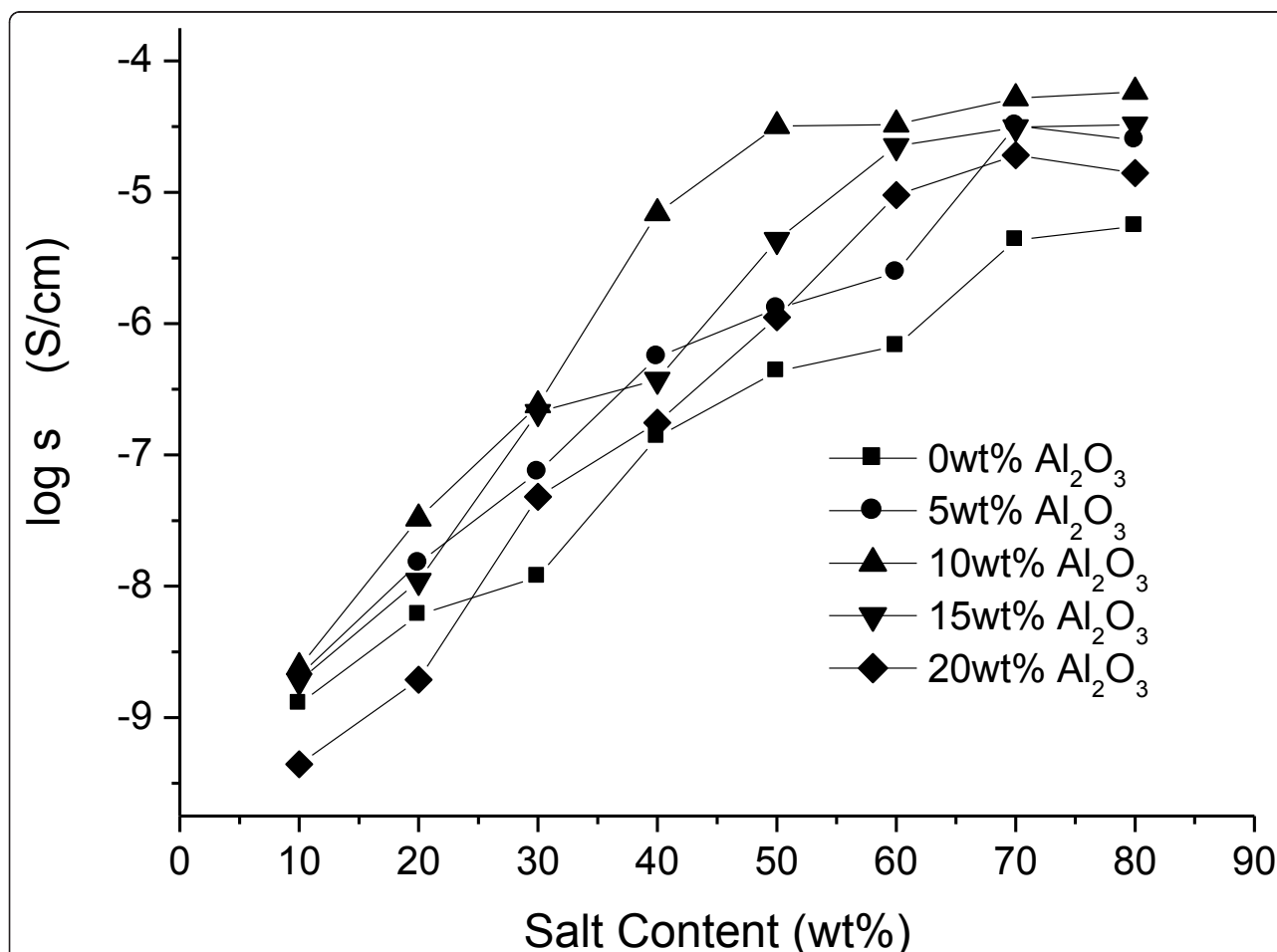
Ionic conductivity of the sample was measured by Gamry Instruments' (Warminster, PA, USA) Reference 600 impedance analyzer. Deconvolution of the composite bands of the Fourier transform infrared [FT-IR] spectra was accomplished by the best fits of constituent Gaussian peaks, and the fractions of salt forms were calculated by the peak fitting program of Origin 7.0 software (OriginLab Corporation, Northampton, MA, USA) to analyze the change of salt forms in SPEs. Scanning electron microscopy [SEM] was also used to observe the morphology of the specimen.

#### Results and discussion

##### Ionic conductivity

##### *Ionic conductivities of PS-based composite SPEs with salt content*

Figure 1 shows the ionic conductivities of PS-based SPEs with 0, 5, 10, 15, and 20 wt.%  $\text{Al}_2\text{O}_3$  and various salt contents. In the common SPEs, the ionic conductivity increased with the salt content up to its peak and then the ionic conductivity decreased because the



**Figure 1** Ionic conductivities of PS-based composite SPEs. PS-based composite SPEs with 0, 5, 10, 15, and 20 wt.%  $\text{Al}_2\text{O}_3$  and various salt contents.

polymer mobility decreased and  $T_g$  of the polymer increased as the salt content increased. However in PS-based composite SPEs, there is no decrease in the ionic conductivity because PS does not contribute to the dissociation of salts and transport of cations. The transport of cations is done by ion-hopping through the ion percolation path made of high content of salt instead of segmental motion, so the ionic conductivities increased with salt content.

Moreover,  $\text{Al}_2\text{O}_3$  can dissolve the lithium salt instead of the polar groups in the polymer matrix using Lewis acid-base interactions between the surface group of  $\text{Al}_2\text{O}_3$  and salt [10]. The sample consisting 70 wt.% salt and 10 wt.%  $\text{Al}_2\text{O}_3$  shows the highest ionic conductivity of  $5.83 \times 10^{-5} \text{ Scm}^{-1}$ .

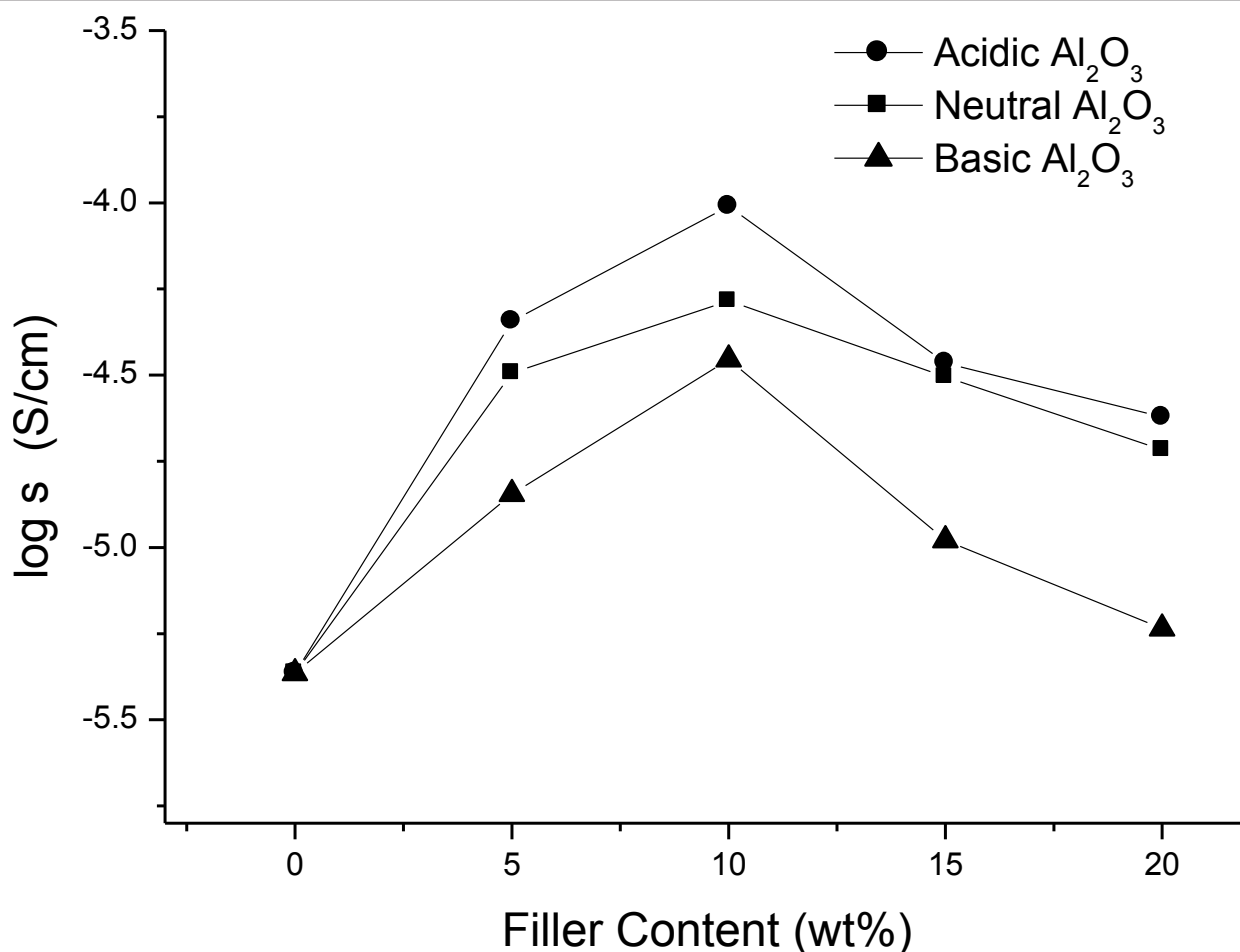
#### **Ionic conductivity of PS-based composite SPE according to $\text{Al}_2\text{O}_3$ type and content**

Figure 2 shows the ionic conductivities of PS-based composite SPEs consisting 70 wt.% salt and different types of  $\text{Al}_2\text{O}_3$ . The ionic conductivity increased up to 10 wt.%  $\text{Al}_2\text{O}_3$  and then decreased, irrespective of the  $\text{Al}_2\text{O}_3$  type. As the content of  $\text{Al}_2\text{O}_3$  increased over 10

wt.%, the aggregates of  $\text{Al}_2\text{O}_3$  was observed in all types of  $\text{Al}_2\text{O}_3$ . This is related to the decrease in ionic conductivity at above 10 wt.%  $\text{Al}_2\text{O}_3$ . Among the samples, the maximum ionic conductivity was found for SPE with acidic  $\text{Al}_2\text{O}_3$ , and the ionic conductivity decreased in the order of SPEs with acidic, neutral, and basic  $\text{Al}_2\text{O}_3$ . This tendency may be related to the number of free ions by dissociation of salt. Salt can be dissociated by the interaction between salt anions and surface OH groups of  $\text{Al}_2\text{O}_3$ . Acidic  $\text{Al}_2\text{O}_3$  has had the most OH groups which interact with salt, so the SPE having acidic  $\text{Al}_2\text{O}_3$  can have the highest free-ion numbers. Neutral  $\text{Al}_2\text{O}_3$  has had the second amount of surface OH groups, and basic  $\text{Al}_2\text{O}_3$  has had the least surface OH groups. Thus, the ionic conductivity decreased in that order, and the highest ionic conductivity of  $9.78 \times 10^{-5} \text{ Scm}^{-1}$  could be obtained at 10 wt.% acidic  $\text{Al}_2\text{O}_3$ .

#### **FT-IR evidence of dissociated ions**

In the polymer-in-salt system, ion clouds made of ion aggregates and ion pairs play an important role in ion conduction [11], so it is necessary to investigate the



**Figure 2** Ionic conductivities of PS-based composite SPEs with different types of  $\text{Al}_2\text{O}_3$ .

**Table 1 Some band assignments for triflate species**

Band	Wave number (cm <sup>-1</sup> )	Assignment
$\nu_s(\text{SO}_3)$	1,032	Free Tf ions, solvent-separated pairs
	1,040	Ion pairs ( $\text{LiTf}$ ), $\text{LiTf}_2^-$ , $\text{LiTf}_3^{2-}$
	1,051	$\text{Li}_2\text{Tf}^+$ aggregate
	1,062	$\text{Li}_3\text{Tf}^{2+}$ aggregate

change of salt form of the SPE films as salt concentrations increase. FT-IR spectra have confirmed the presence of ion pairs and aggregates in SPEs based upon poly(propylene oxide) [12-16] and PEO [17-24]. A clear distinction between free (dissociated) ions, contact ion pairs, and more aggregates may be observed in the vibrational spectra of the internal mode of anions, such as the triflate anion [ $\text{Tf}^-$ ]. Ion association occurs at the  $\text{SO}_3$  end of the anion; thus, the symmetric  $\text{SO}_3$  stretching mode is highly sensitive to change in the coordination state of the anion. Band fitting of these regions has provided information pertaining to the types of aggregation and strengths of ionic interactions occurring in the SPEs.

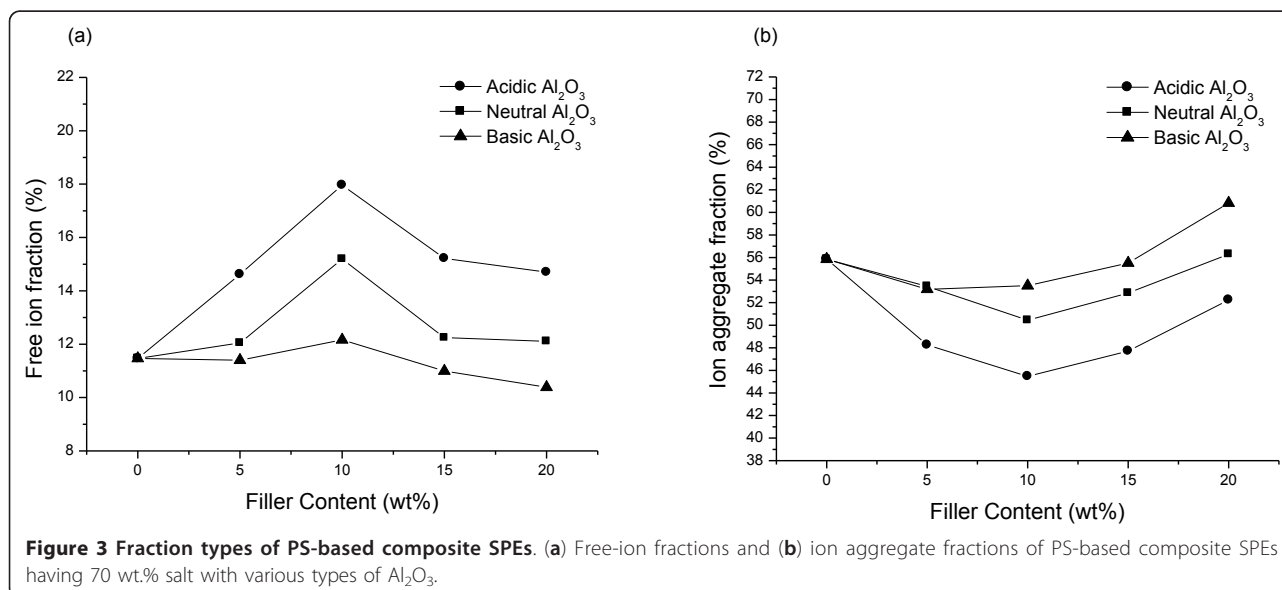
Above a certain salt concentration, the symmetric  $\text{SO}_3$  stretching mode is found to consist of two or more peaks. The different anion environments may be attributed to ion association, in consideration of the nondegenerate  $A_1$  symmetry of this mode. The symmetry of an anion is lowered by coordination to a cation. Band fitting of the  $\text{SO}_3$  regions reveals the peak components which arise from various ion aggregates. Higher frequency components, corresponding to higher aggregates, may be observed with further increase in salt concentration [25]. Assignments for bands observed in

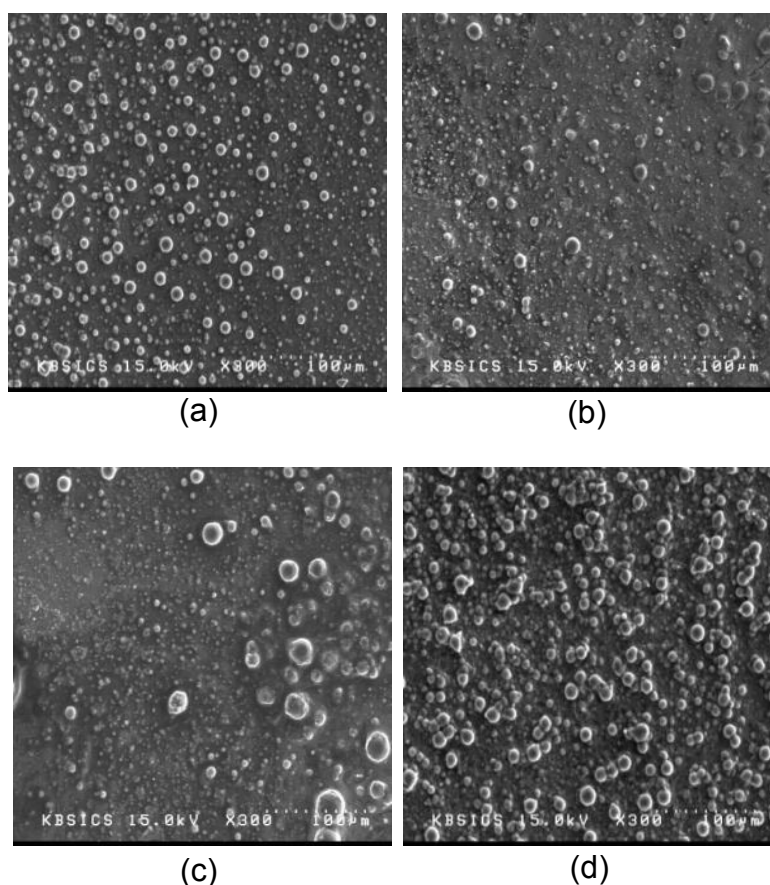
the symmetric  $\text{SO}_3$  stretching regions are summarized in Table 1[18,26].

When  $\text{Al}_2\text{O}_3$  is added, the anions have greater affinity toward the  $\text{Al}_2\text{O}_3$  surface acid groups than the cations. Due to the polarizability of the  $\text{Tf}^-$ , a strong affinity can be expected between the  $\text{Tf}^-$  and the  $\text{Al}_2\text{O}_3$  surface acid groups. It results in the dissociation of the salt and makes the cations free [10,27]. The free-ion and ion aggregate fractions of PS-based composite SPEs having 70 wt.% salt with various types of  $\text{Al}_2\text{O}_3$  are shown in Figure 3. As shown in Figure 3, for all cases, the free-ion fractions of SPE consisting 70 wt.% salt increased until the content of  $\text{Al}_2\text{O}_3$  reached 10 wt.%. By adding more  $\text{Al}_2\text{O}_3$ , the free-ion fraction decreased. SPE with acidic  $\text{Al}_2\text{O}_3$  having the most OH groups which interact with salt had the highest free-ion fraction. The free-ion fraction decreased in the order of SPEs with acidic, neutral, and basic  $\text{Al}_2\text{O}_3$ . This tendency was similar to that of the ionic conductivity. From this result, it could be known that the ionic conductivity was mainly influenced by the free-ion fraction. Also, the highest ionic conductivity could be obtained in the case of SPE with 10 wt.% acidic  $\text{Al}_2\text{O}_3$  whose free-ion fraction was the highest and ion aggregate fraction was the lowest.

#### SEM images

Figure 4 shows the SEM images of PS-based composite SPEs with  $\text{Al}_2\text{O}_3$  content. From the SEM images, we can see that the fillers are well dispersed, and there are no aggregates of  $\text{Al}_2\text{O}_3$  until 10 wt.%  $\text{Al}_2\text{O}_3$  is reached, but as more  $\text{Al}_2\text{O}_3$  was added, the aggregates of fillers which might disturb the ion transport were observed. Thus, the ionic conductivity of PS-based composite





**Figure 4** SEM images of PS-based composite SPEs. PS-based composite SPEs with (a) 5 wt.%, (b) 10 wt.%, (c) 15 wt.%, and (d) 20 wt.%  $\text{Al}_2\text{O}_3$  contents at a magnification of  $\times 300$ .

SPEs, as shown in Figure 2, increased up to 10 wt.%  $\text{Al}_2\text{O}_3$ , and then the ionic conductivity decreased.

## Conclusions

Composite SPEs based on PS,  $\text{LiCF}_3\text{SO}_3$ , and  $\text{Al}_2\text{O}_3$  were prepared, and the effect of the  $\text{Al}_2\text{O}_3$  type and content on ion conduction properties of SPEs was investigated. As the salt content increased, the ionic conductivities increased continuously. In contrary of the common SPE, PS-based composite SPE has no decrease in ionic conductivity because PS does not contribute to the dissociation of salts and transport of cations. As the  $\text{Al}_2\text{O}_3$  content increased, the ionic conductivity increased until the content of  $\text{Al}_2\text{O}_3$  reached 10 wt.%. Then, the sample consisting 70 wt.% salt and 10 wt.%  $\text{Al}_2\text{O}_3$  shows the highest ionic conductivity of  $5.83 \times 10^{-5} \text{ Scm}^{-1}$ . The maximum ionic conductivity was found in SPE with acidic  $\text{Al}_2\text{O}_3$ . The ionic conductivity decreased in the order of SPEs with acidic, neutral, and basic  $\text{Al}_2\text{O}_3$ . This tendency may be related to the number of free ions by dissociation of salt. The SEM images show that the fillers are well

dispersed, and there is no aggregate of fillers until 10 wt.%  $\text{Al}_2\text{O}_3$  is reached. On the other hand, as more  $\text{Al}_2\text{O}_3$  contents were added, the aggregates of fillers appeared. It seems that the aggregates of fillers disturb the ion transport, so the ionic conductivity increased up to 10 wt.%  $\text{Al}_2\text{O}_3$ , and then the ionic conductivity decreased. The highest ionic conductivity of  $9.78 \times 10^{-5} \text{ Scm}^{-1}$  could be obtained at 10 wt.% acidic  $\text{Al}_2\text{O}_3$ .

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## Authors' contributions

YJL and YHA carried out the measurements and analysis of data. NJJ commented on various points and drafted the manuscript. All authors read and approved the final manuscript.

## Competing interests

The authors declare that they have no competing interests.

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